

NASA'S EARTH SYSTEM OBSERVATORY— ATMOSPHERE OBSERVING SYSTEM

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ABSTRACT

NASA has begun pre-formulation studies for the Earth System Observatory, a constellation of observatories designed to implement the recommendations of the 2017 NASA Earth Science Decadal Survey. For the atmosphere, the Atmosphere Observing System (AOS) will focus on aerosols, clouds, convection, and precipitation, their mutual interactions, and interactions with atmospheric radiation. AOS consists of two projects, one in an inclined orbit to measure sub-daily variability across all times of day, particularly for deep convection and its attendant high clouds, and one in a polar orbit to provide globally distributed observations with more advanced capabilities, coupling to radiation, and an eye toward continuity of key cloud and aerosol data records. This paper describes the AOS science objectives, the architectures of the two projects, planned sub-orbital activities, and relevant applications.

Index Terms— Aerosols, clouds, convection, precipitation, radiation

1. INTRODUCTION

The NASA Earth Science Decadal Survey [3] recommended a range of Earth Observing programs to be advanced by NASA over the following decade. Included among those recommendations were a set of 5 designated observables (DOs) focused on aerosols (A); clouds, convection, and precipitation (CCP); mass change; surface biology and geology; and surface deformation and change. From late 2018 through 2020, NASA conducted studies to explore architectures that could implement the DOs within cost and schedule constraints. In response to those studies, NASA announced the Earth System Observatory (ESO) (<https://science.nasa.gov/earth-science/earth-system-observatory/>), which will implement the five DOs as a coordinated constellation. Because aerosols, clouds, and precipitation are fundamentally linked at the microphysical scale, the aerosol and CCP DOs were studied (under the name ACCP) and are being implemented as a pair of joint missions addressing aspects of the combined science under the preliminary name, the Atmosphere Observing System (AOS), <https://aos.gsfc.nasa.gov/>. This paper summarizes the AOS science objectives, the spaceborne architecture and suborbital program, and expected applications.

2. AOS SCIENCE OBJECTIVES

The Decadal Survey identified a range of science objectives related to A and CCP, rating them as important, very important, or most important. The ACCP study team focused on three of the “most important” science objectives related to convective formation processes, pollution processes and distribution, and climate feedback and sensitivity to formulate a set of related ACCP science objectives (Table 1) that are also adopted by AOS.

Table 1: AOS Science Objectives

Low clouds: Determine the sensitivity of boundary layer cloud bulk physical, microphysical and radiative properties to large-scale and local environmental factors including thermodynamic and dynamic properties.

High clouds: Relate the vertical structure, horizontal extent, ice water path, microphysical and radiative properties of convectively generated high clouds to convective vertical transport and large-scale high clouds to environmental factors.

Convective storm systems: Relate vertical motion within convective storms to their a) cloud and precipitation structures, b) microphysical properties, c) latent heating, d) local environment conditions, e) ambient aerosol loading, and d) diurnal variability.

Cold clouds and precipitation processes: Detect and quantify the vertical structure, cloud bulk, microphysical and radiative properties (including mixed-phase precipitation and snowfall) of high-latitude cloud systems.

Aerosol attribution and air quality: Quantify optical and microphysical aerosol properties in the boundary layer and free troposphere to improve process understanding, estimates of aerosol emissions (including diurnal variability), speciation, and predictions of near-surface particulate concentrations.

Aerosol wet removal, vertical redistribution, and processing: Relate the vertical structure of aerosol properties to cloud and precipitation properties to improve understanding of processes impacting aerosol vertical transport, removal, overall lifecycle, aerosol processing.

Aerosol direct effects: Reduce uncertainties in estimates of clear and all-sky shortwave direct radiative effects (DRE) and provide measurements to constrain the

anthropogenic contribution to the DRE. Quantify vertically resolved aerosol radiative heating rates to improve understanding of the impacts of absorbing aerosol on atmospheric stability.

Aerosol indirect effects: Provide measurements to constrain process-level understanding of aerosol-cloud interactions to improve estimates of aerosol indirect radiative forcings.

3. ORBITAL ARCHITECTURE

To explore potential observing systems to address the ACCP science objectives, the ACCP study team identified a list of required geophysical variables and their characteristics in a science and applications traceability matrix (https://aos.gsfc.nasa.gov/docs/ACCP_SATM_Rel_Candidate_G.pdf). The team explored more than 50 architectures and recommended a two-orbit solution to NASA HQ (https://aos.gsfc.nasa.gov/docs/ACCP_Science_Narrative-2021.07.19.pdf) that became the baseline AOS spaceborne architecture. AOS consists of two projects (Fig. 1), currently in the mission concept study phase known as Pre-Phase A. The first project, with an estimated launch date of mid 2028 and denoted AOS-I, includes sensors in an inclined (nominally 55°), precessing orbit to deliver early science focused on sub-daily time scales, with an emphasis on deep convection [4], high clouds [5], and aerosols [2]. The second project, with an estimated launch in early 2030 and denoted AOS-P, includes advanced sensors in a polar orbit, nominally at an 0130 equatorial crossing time, focused on globally distributed observations to assess aerosol-cloud-precipitation-radiation interactions and their role in climate and climate change. These two projects are covered in the following subsections. An additional measurement component of AOS is a sustained suborbital program, described in section 4, to address science that cannot be addressed from space or can be addressed better from airborne or ground-based observing systems.

3.1. Inclined orbit

The baseline AOS-I project includes two satellites carry a W-band radar, a Ku-band Doppler radar using the Displaced Phase Center Antenna (DPCA) approach [1], a two-frequency (532 and 1064 nm) backscatter lidar, a high frequency (nominally 89 to 325 GHz and possibly higher) passive microwave radiometer, a multi-angle polarimeter [channels from ultra violet (UV) to shortwave infrared (SWIR)], and a pair of stereo visible-frequency cameras designed to use measurements approximately 45 seconds apart to infer cloud or aerosol plume top horizontal and vertical air motions. The cameras drive the need for the two spacecraft.

As part of pre-Phase A, the team is examining potential international contributions to the inclined orbit from the Japan Aerospace Exploration Agency (JAXA) and the Centre National d'Etudes Spatiales (CNES). JAXA may provide a wide-swath Ku-band radar with nadir DPCA Doppler



Figure 1. The AOS architecture consisting of a polar orbit (AOS-P1) and inclined orbit (AOS-I1 and AOS-I2).

capability while CNES may provide a pair of passive microwave radiometers (89-325 GHz) for time-differenced brightness temperatures to infer evolving microphysical properties and vertical mass flux.

3.2. Polar orbit

The baseline AOS-P project includes a single satellite carrying W- and Ka-band DPCA Doppler radars, a passive microwave radiometer (118-880 GHz), high spectral resolution lidar (HSRL at 532 nm, backscatter at 1064 nm), multi-angle polarimeter (similar to AOS-I), a UV to SWIR shortwave spectrometer, and a Canadian Space Agency (CSA) contributed longwave and far infrared spectrometer. The CSA is also exploring the addition of another satellite in the polar orbit carrying aerosol and moisture limb sounders, with a focus on properties of the upper troposphere and lower stratosphere.

4. SUB-ORBITAL SCIENCE

The AOS includes a suborbital science component designed to collect data for investigations that cannot be adequately addressed from spaceborne measurements alone. Satellite “blind zones” can come into view with airborne or surface-based instrumentation that provides higher spatial resolution and/or views from below overlying cloud and precipitation layers. Surface-based measurements also provide temporal continuity that will be lacking from the low-earth-orbit measurements.

The ESO-AOS suborbital program is organized around three science themes with highly synergistic objectives. Those themes include low clouds and aerosol-cloud-radiation interactions; deep convection and high clouds; and aerosol-cloud-radiation interaction, aerosol attribution, and aerosol redistribution. These science themes have numerous interrelated aspects. Investigation of these themes will also

require many measurements that are required for development and evaluation of the satellite-based algorithms, and for calibration/validation of the orbital instruments.

Implementation strategies for the suborbital program include a mix of leveraging and augmenting existing surface-based measurement capabilities, partnering in relevant external field campaigns, and leading a small number of major airborne field campaigns. Existing operational or research measurement sites may be augmented by deployment of instrumentation such as research radars, profilers, in-situ aerosol and precipitation instrumentation, and research aircraft overflying heavily instrumented surface sites.

Multi-aircraft campaigns will likely include a mix of satellite-simulator remote-sensing instruments and in-situ measurements. They will be designed to address complementary themes. For example, a multi-aircraft program from a coastal or tropical island location may include flights measuring aerosol characteristics, cloud and precipitation initiation and aerosol interactions in shallow oceanic cumulus, and the growth and evolution of deep tropical convection systems.

5. APPLICATIONS

Due to rapid changes in the Earth system and the need to thrive on our changing planet, the transition of scientific research to applications is essential. A focus on the cross-benefit of science and applications through partnerships between scientists and stakeholders can reduce the timelines from analysis to decision and increase the value and benefit of NASA's Earth Science missions. The AOS Applications Team solicits, synthesizes, and articulates stakeholder needs throughout the study and development phases of the mission to ensure that applications are considered to the greatest extent possible in mission design.

The applications activities have centered around stakeholder community engagement, the development of a Community Assessment Report (CAR), internal participation on science and engineering working groups, and discussion with other Designated Observable mission teams. Stakeholder feedback has been solicited and gathered through thematically focused community workshops, focus groups, individual interviews, and surveys. The synthesis of this information, in addition to knowledge acquired from previous mission application activities, form the basis for identifying potentially high-impact applications (Fig. 2) and supporting the development of the CAR. The goal of the AOS CAR is to provide relevant information on stakeholder organizations and their needs that can be used to inform AOS design and instrument considerations, algorithm needs, data latency, and data product generation. Throughout mission development, the applications effort will focus on engaging early adopters, conducting trainings, and continuing to engage with

High-impact enabled applications lead to direct societal impacts
Severe Weather: Novel observations of clouds, aerosols, and precipitation lead to a better understanding of the timing, intensity, and severity of storms, and improved forecasting skill over high-risk areas
Climate Modeling: Reduced uncertainties in cloud and aerosol feedbacks enable improved climate modeling capabilities on a variety of temporal scales
Water Resources, Agriculture and Drought: Improved precipitation estimates for agricultural modeling inform crop yields and water resource allocation
Atmospheric Disasters Monitoring and Modeling: Observations of volcanic plumes, wildfire smoke, and dust support aviation safety and improve air quality modeling
Air Quality Forecasting and Public Health: Discerning aerosol subtypes informs air quality monitoring and health studies

Figure 2. Example of applications that could take full advantage of AOS measurements and would have high and immediate impact in the community.

stakeholder communities to further refine opportunities, challenges, and needs.

6. REFERENCES

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